

DUV-CAPABLE MICROSCOPE OBJECTIVE
WITH PARFOCAL IR FOCUS

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FIELD OF THE INVENTION

The invention concerns a DUV-capable microscope objective
having the features of the preamble of independent Claim 1.

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BACKGROUND OF THE INVENTION

The resolution of a microscope depends substantially on the wavelength of the
illumination light used. Conventional microscopes are operated with light in the
visible wavelength region (abbreviated "VIS"). In order to resolve extremely small
structures, for example on wafers or circuits in the semiconductor industry,
imaging at shorter wavelengths in the deep-ultraviolet region of the light spectrum
(abbreviated "DUV") is required. The microscope image is made visible using a
TV camera that is sensitive to the DUV light.

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The materials in conventional VIS optics are not transparent to DUV. DUV
operation therefore requires optics constructed from special materials, for example
prisms, beam splitters, and tube lenses, as well as objectives that are corrected for
DUV wavelengths. In order to meet future requirements of the semiconductor
industry, a DUV microscope preferably has capabilities for switching between
VIS and DUV optics and the respective associated illuminating systems, in which
a switchover between VIS and DUV objectives is also made.

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In addition, the autofocus function of a microscope is an essential requirement in
the semiconductor industry, since automatic (and therefore more rapid) focusing
can considerably increase the number of features examined per hour as compared
to manual focusing.

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Known IR laser autofocus systems are greatly superior in this context, because of their higher focusing speed, to other autofocus systems (e.g. TV autofocus systems) which operate at the particular wavelength being imaged. The autofocus wavelength is shifted into the IR wavelength region so that the IR autofocus light can easily be coupled in, for example via a dichroic splitter in the imaging beam path. This prevents any loss of portions of the illuminating or imaging beam in the VIS or DUV/UV wavelength regions.

10 The ability for a DUV microscope also to be operated with a fast IR autofocus system is therefore a pressing need in the semiconductor industry. IR autofocus-capable objectives already exist for the VIS region, but not yet for the DUV region. In particular, a well-corrected DUV objective with high magnification and a large aperture is necessary in order to image extremely small features.

15 DE 39 15 868 C2 describes a 100X/0.87 DUV objective with a focal length of approximately 1.5 mm and a numerical aperture of 0.87. It comprises at least eleven lenses, which constitute a front lens group and a rear lens group. The rear lens group is configured as a shifting element. By displacing the shifting element, it is possible to change the air gap from the front lens group and thus adjust the usable wavelength region in the DUV and in a portion of the visible spectrum. The objective's correction for spherical aberration, however - for example at the common DUV illumination wavelength of 248 nm - is not particularly good. The greatest disadvantage, however, is that the objective does not have a parafocal focus in the near infrared wavelength region (abbreviated "IR"), i.e. at IR wavelengths > 760 nm. The objective is therefore not suitable for use on a DUV microscope having an IR laser autofocus apparatus that works with IR wavelengths.

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SUMMARY OF THE INVENTION

It is therefore the object of the present invention to describe a very well-corrected DUV objective having a numerical aperture of at least 0.80 and a short focal
5 length, which is IR autofocus-capable.

This object is achieved by a ~~DUV~~ objective that has the features of Claim 1.
Advantageous embodiments of the objective are recited in the dependent claims.

10 An objective according to the present invention comprises a system of lenses made of quartz glass and fluorite. It has a focus in a wavelength band around a DUV wavelength λ_{DUV} selected for DUV illumination, and the same focus for an IR wavelength λ_{IR} in the near IR region. It was hitherto considered impossible to compute a focus combination of this kind, since with usual computation formulas
15 and current methods and theories of optical computation an objective of this kind, focusing in both IR and DUV, was believed to be impossible to realize. The criteria used for evaluating the focusing properties are the so-called spectral image locus curves of an objective, which involve a comparison between the image locus curve for the paraxial region and the image locus curve for full aperture. The
20 spectral image locus curves indicate the focal points of the objective as a function of wavelength.

It has been found, surprisingly, that by way of a specific configuration of the (penultimate element of an objective) the aforementioned two spectral image locus
25 curves of an objective can be made almost coincident over the entire wavelength region from DUV to IR: according to the present invention, this penultimate element is of concave configuration on both sides, and its object-side outer radius is much smaller than the image-size outer radius.

30 Good agreement between the two image locus curves indicates good correction of spherical aberration. Depending on the exemplary embodiment of the objective according to the present invention, the penultimate element is constructed either as

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a doublet or a triplet, or as a double in combination with an individual lens, or as individual lenses only. As materials, combinations of quartz glass and fluorite or of quartz glass and lithium fluoride can be used. Specific sequences of materials prove advantageous in this context. In one advantageous embodiment, for example, a doublet has the material sequence quartz glass/fluorite in the imaging direction, and a triplet has the material sequence quartz glass/fluorite/quartz glass or quartz glass/lithium fluoride/quartz glass in the imaging direction.

As a result of the size relationship according to the present invention among the outside radii, the imaging beam that up to that point has been slightly deflected by the preceding lenses or cemented groups is strongly refracted. This kind of beam deflection violates the rule ordinarily applied in optical computation that the beam must always be modified smoothly at each imaging element. For example, a sharp transition in the beam makes the objective highly sensitive to tolerances, so that an objective of this kind is difficult to produce or makes stringent demands in terms of production.

On the other hand, however, only with ^{Next to the Last.} a penultimate element having this particular shape did it prove possible to achieve the same focus both for a region around a DUV wavelength λ_{DUV} and for an IR wavelength λ_{IR} . If the relevant penultimate element is equipped, in an objective according to the present invention, with a moderate shape so that the previously deflected beam profile is smoothed again, then both the good correction and the focus for the IR wavelength λ_{IR} are lost.

The spectral image locus curves of an objective according to the present invention have, at the selected DUV wavelength λ_{DUV} , a minimum which indicates the focal point for that wavelength λ_{DUV} . In the IR wavelength region, the image locus curve has a zero transition at the desired IR wavelength λ_{IR} . In other words, the focal points of the DUV wavelength λ_{DUV} and of the IR wavelength λ_{IR} are the same, i.e. confocal. In addition, the paraxial image locus curve and image locus

curve for full aperture are almost identical over the spectral range from λ_{DUV} to λ_{IR} .

Since the spectral image locus curve extends, around its minimum at λ_{DUV} , within
5 the depth of field in a wavelength band $\lambda_{\text{DUV}} \pm \Delta\lambda$ (where $\Delta\lambda = 8 \text{ nm}$), this entire
DUV wavelength band can be used for imaging. This offers the advantage, as
compared to a monochromatic focus in the DUV, that an expensive laser is not
necessary for illuminating the microscope, but instead that a more economical
DUV spectral lamp with a finite line width is sufficient. It is possible, however, to
10 use any laser line that falls in the vicinity of the DUV wavelength band, since that
laser line is monochromatic and monochromatic illumination will eliminate any
chromatic errors in the image.

If a specific DUV wavelength is then taken as the basis for calculating the DUV
focus, with a penultimate element according to the present invention it is in fact
possible to construct an objective to match each of a number of IR focus
wavelengths. As a result, a respective IR autofocus-capable DUV objective can be
described for IR wavelengths = 760 nm, i.e. to match a plurality of possible IR
laser diodes for an IR laser autofocus system.

The objectives according to the present invention have short focal lengths of no
more than 1.6 mm, a large aperture of at least 0.9, and good correction of all
image errors. The working distance is between approximately 0.19 and 0.22 mm,
depending on the exemplary embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter of the invention is described with reference to
the embodiments shown in the drawings.

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- FIG. 1 shows a section through a first objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 248$ nm and an IR focus at $\lambda_{\text{IR}} = 760$ nm;
- FIG. 2 shows a section through a second objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 248$ nm and an IR focus at $\lambda_{\text{IR}} = 825$ nm;
- FIG. 3 shows a section through a third objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 248$ nm and an IR focus at $\lambda_{\text{IR}} = 885$ nm;
- FIG. 4 shows a section through a fourth objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 248$ nm and an IR focus at $\lambda_{\text{IR}} = 905$ nm;
- FIG. 5 shows Table 1 having the design data for the first objective of FIG. 1;
- FIG. 6 shows Table 2 having the design data for the second objective of FIG. 2;
- FIG. 7 shows Table 3 having the design data for the third objective of FIG. 3;
- FIG. 8 shows Table 4 having the design data for the fourth objective of FIG. 4;
- FIG. 9 shows the spectral image locus curves for the first objective of FIG. 1;
- FIG. 10 shows the spectral image locus curves for the second objective of FIG. 2;
- FIG. 11 shows the spectral image locus curves for the third objective of FIG. 3;

- FIG. 12 shows the spectral image locus curves for the fourth objective of FIG. 4;
- 5 FIG. 13 shows a section through the tube lens system, tuned to $\lambda_{\text{DUV}} = 248 \text{ nm}$, used with the objectives of FIGS. 1 through 4;
- FIG. 14 shows Table 5 having the design data for the tube lens system of FIG. 13;
- 10 FIG. 15 shows the schematic configuration of the beam path between the objective, tube lens system and IR autofocus system;
- FIG. 16a shows the astigmatism for the compensation system comprising the objective of FIG. 4 and the tube lens system of FIG. 13;
- 15 FIG. 16b shows the spherical aberration for the compensation system comprising the objective of FIG. 4 and the tube lens system of FIG. 13;
- FIG. 16c shows the deviation from the sine condition for the compensation system comprising the objective of FIG. 4 and the tube lens system of FIG. 13;
- 20 FIG. 17 shows a section through a fifth objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 266 \text{ nm}$ and an IR focus at $\lambda_{\text{IR}} = 760 \text{ nm}$;
- 25 FIG. 18 shows a section through a sixth objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 266 \text{ nm}$ and an IR focus at $\lambda_{\text{IR}} = 785 \text{ nm}$;
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- FIG. 19 shows a section through a seventh objective according to the present invention having a DUV focus at $\lambda_{\text{DUV}} = 266 \text{ nm}$ and an IR focus at $\lambda_{\text{IR}} = 845 \text{ nm}$;
- 5 FIG. 20 shows Table 6 having the design data for the fifth objective of FIG. 17;
- FIG. 21 shows Table 7 having the design data for the sixth objective of FIG. 18;
- 10 FIG. 22 shows Table 8 having the design data for the seventh objective of FIG. 19;
- FIG. 23 shows the spectral image locus curves for the fifth objective of FIG. 17;
- 15 FIG. 24 shows the spectral image locus curves for the sixth objective of FIG. 18;
- FIG. 25 shows the spectral image locus curves for the seventh objective of FIG. 19;
- 20 FIG. 26 shows a section through a tube lens system, tuned to $\lambda_{\text{DUV}} = 266 \text{ nm}$, used with the objectives of FIGS. 17 through 19.
- 25 FIG. 27 shows Table 9 having the design data for the tube lens system of FIG. 26.

DETAILED DESCRIPTION OF THE INVENTION

- 30 The objectives in FIGS. 1 through 4 are all corrected for a DUV wavelength region $\lambda_{\text{DUV}} = 248 \text{ nm} \pm 8 \text{ nm}$, and differ in terms of the IR focus wavelengths indicated. The objectives in FIGS. 17 through 19 are all corrected for a DUV

wavelength region $\lambda_{\text{DUV}} = 266 \text{ nm} \pm 8 \text{ nm}$, and differ in terms of the IR focus wavelengths indicated. The field-of-view (FOV) number for all the exemplary embodiments is 11. The working distance is between 0.19 and 0.22 mm depending on the exemplary embodiment.

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Viewed in the direction of the light, the exemplary embodiments cited share, in principle, the following schematic configuration:

- a converging individual first lens L1 made of quartz glass as the front lens;
- 10 - a converging individual second lens L2 made of fluorite;
- a first doublet comprising a diverging third lens L3 made of quartz glass and a converging fourth lens L4 made of fluorite;
- a first triplet L5+L6+L7 combined of a fifth lens L5 made of fluorite, a sixth lens L6 made of quartz glass and a seventh lens L7 made fluorite
- 15 - a second triplet L8+L9+L10 combined of a eighth lens made of quartz glass and a ninth lens made of fluorite and a tenth lens made of quartz glass;
- a converging lens group L11 with a configuration that differs depending on the exemplary embodiment, either as an individual eleventh lens L11 or as a doublet combined of two lenses L11a+L11b or as an individual lens L11a
- 20 followed by a doublet combined of two lenses L11b+L11c;
- a diverging element according to the present invention, which is concave on both sides and whose object-side outer radius is much smaller than the image-side outer radius, and which can be differently configured depending on the exemplary embodiment, e.g. as a diverging doublet combined of two lenses L12a+L12b or as a triplet combined of three lenses
- 25 L12a+L12b+L12c;
- a diverging doublet L13a+L13b combined of a converging lens L13a made of quartz glass and a diverging lens L13b made of fluorite.

30 The individual exemplary embodiments and the variants of the schematic configuration recited above will be described below. In the sectioned drawings, an object 1 is in focus. Of the lenses on an optical axis 11, L1 is always a front lens.

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The tables having the design data, and the spectral image locus curves, are indicated in each case when the examples are described. In the Tables having the design data, surface 1 designates in each case the position of object 1 in focus. The subsequent surfaces are continuously numbered in sequence.

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The spectral image locus curve for the paraxial region is depicted in each case as a dotted line, and the spectral image locus curve for the full aperture in each case as a solid line. The image locus curves each exhibit a minimum at a DUV wavelength λ_{DUV} that defines a zero line, as well as a zero transition at an IR wavelength λ_{IR} . A DUV wavelength band within which the objective is in focus is defined in each case around the minimum within the depth of field ($\lambda_{\text{DUV}} \pm 8 \text{ nm}$). The zero transition designates a focus at the IR wavelength λ_{IR} that is parfocal with the DUV focus.

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The 125X/0.90 objective depicted in FIG. 1 has a focal length of 1.60 mm, a focus for a DUV wavelength $\lambda_{\text{DUV}} = 248 \pm 8 \text{ nm}$, and a focus for an IR wavelength $\lambda_{\text{IR}} = 760 \text{ nm}$. It has as the converging lens group a doublet L11a+L11b, and as the diverging penultimate element according to the present invention a diverging doublet L12a+L12b, which comprises a diverging lens L12a made of quartz glass and a converging lens L12b made of fluorite. It is characterized by a longer focal length than the other exemplary embodiments. Design data for the objective are indicated in FIG. 5, and the spectral image locus curves in FIG. 9.

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The 150X/0.90 objective depicted in FIG. 2 has a focal length of 1.33 mm, a DUV focus at $\lambda_{\text{DUV}} = 248 \pm 8 \text{ nm}$, and an IR focus at $\lambda_{\text{IR}} = 825 \text{ nm}$. It has as the converging lens group an individual lens L11, and as a diverging penultimate element according to the present invention a diverging triplet L12a+L12b+L12c made of quartz glass/fluorite/quartz glass. It has slightly greater distortion than the other exemplary embodiments. Design data for the objective are indicated in FIG.

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6, and spectral image locus curves in FIG. 10.

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The 150X/0.90 objective depicted in FIG. 3 has a focal length of 1.33 mm, a DUV focus at $\lambda_{\text{DUV}} = 248 \pm 8$ nm, and a parfocal focus at an IR wavelength $\lambda_{\text{IR}} = 885$ nm. It has as the converging lens group a combination of an individual lens L11a and a doublet L11b+L11c, and as a diverging penultimate element a diverging triplet L12a+L12b+L12c according to the present invention made of quartz glass/fluorite/quartz glass. The objective is well-corrected and relatively insensitive to tolerances. Design data for the objective are indicated in FIG. 7, spectral image locus curves in FIG. 11.

- 10 The 150X/0.90 objective depicted in FIG. 4 has a focal length of 1.33 mm, a DUV focus at $\lambda_{\text{DUV}} = 248 \pm 8$ nm, and a parfocal IR focus at $\lambda_{\text{IR}} = 905$ nm. It has as the converging lens group an individual lens L11, and as a diverging penultimate element a diverging triplet L12a+L12b+L12c according to the present invention made of quartz glass/fluorite/quartz glass. The objective is characterized by low distortion, but it is more sensitive to tolerances than the other exemplary
15 embodiments. Design data for the objective are indicated in FIG. 8, spectral image locus curves in FIG. 12.

- The objectives of FIGS. 1 through 4 cited as examples are calculated for an
20 infinity beam, and together with a tube lens constitute a compensation system for the DUV wavelength region $\lambda_{\text{DUV}} = 248 \text{ nm} \pm 8 \text{ nm}$. FIG. 13 shows a section through the tube lens system used with the objectives according to the present invention. It comprises a converging lens L14 and a doublet L15a+L15b. FIG. 14 shows Table 5 having the pertinent design data for the tube lens system shown in
25 FIG. 13.

- Compensation is always performed for the selected DUV wavelength band $\lambda_{\text{DUV}} \pm \Delta\lambda$, but not for the respective IR wavelength, which is not imaged. This is illustrated by FIG. 15, which shows an image beam beam path 2 proceeding from an
30 object 1. On this beam path, the DUV illumination light passes through an objective 3 to a beam splitter 4. This beam splitter 4 serves as the input and output element for the IR light of an IR laser autofocus system 5. The IR laser light

emerging from IR laser autofocus system 5 via autofocus beam path 6 is deflected at beam splitter 4 to objective 3 and thus toward object 1, and returns in the opposite direction to IR laser autofocus system 5. The DUV light passes through beam splitter 4 and is imaged by a tube lens system 7 in an intermediate image plane 8, at the location of the target of a DUV camera 9. Since the IR light does not arrive at intermediate image plane 8, tube lens system 7 needs to be corrected only for the DUV light.

A different tube lens system compensating for the relevant DUV band must therefore be calculated in each case for objectives that are themselves calculated for different DUV wavelength bands.

A further application of the objectives can be explained with reference to FIG. 15. For example, an offset lens 10 can be inserted between beam splitter 4 and IR laser autofocus system 5. With this, the usable IR autofocus wavelength can be varied by a fixed amount of up to approximately ± 20 nm. As a result, there exists around each IR focus wavelength λ_{IR} a wavelength region in which the IR autofocus system can still be used. For example, with an objective for which an IR focus wavelength $\lambda_{IR} = 825$ nm is specified (cf. FIG. 2), it is possible to autofocus using an IR autofocus system having a laser wavelength between 805 nm and 845 nm.

This means that the even the objective of FIG. 1 is IR autofocus-capable. This objective has a parfocal focus only for an IR wavelength $\lambda_{IR} = 760$ nm, which is not yet entirely assignable to the IR region, since according to standards the IR region begins at 780 nm. But with the use of an offset lens in the autofocus beam path, the objective can nevertheless be operated with a laser wavelength between 740 nm and 780 nm, and thus also at an IR wavelength (780 nm).

The width of the IR region around the specified IR focus wavelength that is usable with an objective depends on the slope of the spectral image locus curves at the zero transition at the IR focus wavelength. The flatter the zero transition, the

wider the usable IR wavelength region for selection of the autofocus laser. This means that the wavelength region of interest for IR autofocus operation can be covered with a relatively small number of objectives.

5 FIGS. 16a through 16c show, by way of example, the correction of the compensation system (comprising the objective of FIG. 4 and the tube lens of FIG. 13) for each corrected DUV wavelength region, based on the average wavelength 248 nm and the two wavelengths spaced 8 nm away, i.e. 240 nm and 256 nm. FIG. 16a shows astigmatism as a function of object height y' (= distance of an object point from the optical axis) in the form of the sagittal image surface (solid line) and the meridional image surface (dashed line). FIG. 16b shows the spherical aberration z as a function of image-side aperture. FIG. 16c shows the deviation from the sine condition as a function of image-side aperture. It is evident that the compensation system is very well-corrected. The same also applies in similar fashion to the other exemplary embodiments.

The objectives in FIGS. 17 through 19 will now be described. They are all corrected for a DUV wavelength region $\lambda_{\text{DUV}} = 266 \text{ nm} \pm 8 \text{ nm}$, and differ in terms of the indicated IR focus wavelengths.

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The 150X/0.90 objective depicted in FIG. 17 has a focal length of 1.33 mm, a DUV focus at $\lambda_{\text{DUV}} = 266 \pm 8 \text{ nm}$, and a parfocal IR focus at $\lambda_{\text{IR}} = 780 \text{ nm}$. It has a special feature in the front part: instead of individual second lens L2 and first doublet L3+L4 of the layout described above, it has a triplet L2+L3+L4 of fluorite/quartz glass/fluorite. The objective furthermore has as the converging lens group a doublet L11a+L11b, and as the diverging penultimate element according to the present invention a diverging triplet L12a+L12b+L12c made of quartz glass/fluorite/quartz glass. The objective is characterized by low distortion and is relatively insensitive to tolerances. Design data for the objective are indicated in FIG. 20, spectral image locus curves in FIG. 23.

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The 150X/0.90 objective depicted in FIG. 18 has a focal length of 1.33 mm, a DUV focus at $\lambda_{\text{DUV}} = 266 \pm 8$ nm, and a parfocal IR focus at an IR wavelength $\lambda_{\text{IR}} = 785$ nm. It has as the converging lens group an individual lens L11a and a doublet L11b+L11c, and as a diverging penultimate element a diverging triplet L12a+L12b+L12c according to the present invention made of quartz glass/fluorite/quartz glass. The objective is characterized by low distortion and is relatively insensitive to tolerances. Design data for the objective are indicated in FIG. 21, spectral image locus curves in FIG. 24.

10 The 150X/0.90 objective depicted in FIG. 19 has a focal length of 1.33 mm, a DUV focus at $\lambda_{\text{DUV}} = 266 \pm 8$ nm, and a parfocal focus at an IR wavelength $\lambda_{\text{IR}} = 845$ nm. It once again has a special feature in the front part: instead of individual lens L2 and doublet L3+L4 of the layout described above, it has a triplet L2+L3+L4 of fluorite/quartz glass/fluorite. It furthermore has as the converging
15 lens group an individual lens L11a and a doublet L11b+L11c, and as the diverging penultimate element according to the present invention has a diverging triplet L12a+L12b+L12c made of quartz glass/lithium fluoride/quartz glass. The use of lithium fluoride instead of fluorite in the diverging triplet reduces the longitudinal chromatic error. The objective therefore has very a well-corrected longitudinal
20 chromatic error and is relatively insensitive to tolerances. Design data for the objective are indicated in FIG. 22, spectral image locus curves in FIG. 25.

The objectives of FIGS. 17 through 19 are also calculated for an infinity beam, and together with a tube lens constitute a compensation system for the DUV
25 wavelength region $\lambda_{\text{DUV}} = 266 \text{ nm} \pm 8$ nm. FIG. 26 shows a section through the tube lens system used with the objectives according to the present invention of FIGS. 17 through 19. It comprises a converging lens L14, a doublet L15a+L15b, and a prism L16. FIG. 27 shows Table 9 having the pertinent design data for the tube lens system of FIG. 26.

The invention has been described in detail with particular reference to certain preferred embodiments thereof, but it will be understood that variations and modifications can be effected within the spirit and scope of the invention.

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PARTS LIST

- 1 Object
- 2 Imaging beam path
- 3 Objective
- 4 Beam splitter
- 5 IR laser autofocus system
- 6 Autofocus beam path
- 7 Tube lens system
- 8 Intermediate image plane
- 9 DUV camera
- 10 Offset lens
- 11 Optical axis

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| L1 - L13 | Lenses of the objectives in FIGS. 1 - 4 and 17 - 18 [sic] |
| L14 - L15 | Lenses of the tube lens systems of FIGS. 13 and 26 |
| L16 | Prism of the tube lens system of FIG. 26 |
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